On the Phase-Error Propagation in Diffusion-Weighted Steady State Free Precession (DW-SSFP) Imaging

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TARGET AUDIENCE: Folks with an interest in high-resolution diffusion-weighted imaging and spin physics of SSFP

INTRODUCTION: There is increasing demand for high-resolution diffusion-weighted MRI at isotropic voxel resolution. However, as one approaches voxel sizes of less than ~1.5x1.5x1.5mm^3, conventional 2D single-shot EPI reaches its limit. In fact, the time spent on diffusion preparation *vs.* the volume information acquired per encoded slice becomes increasingly inefficient. In this case, methods such as diffusion-weighted steady-state free precession (dwSSFP) [1] become an attractive alternative to EPI. In dwSSFP, diffusion-encoding and image data acquisition are intermingled and thus more efficient than 2D EPI for high-resolution 3D imaging. Unlike spin-echoes, echo formation in SSFP is much more complex however and influenced by sequence parameters (α, TR, TE), relaxation (T_1, T_2), and the spin phase immediately before each RF pulse. The influence of sequence parameters and relaxation in dwSSFP is well understood [1,2] and so is the impact of non-linear phase on image reconstruction [3] or FSE [4]. However, the influence of the non-linear phase errors in dwSSFP is much more complex and has not been fully described, thus far. The purpose of this work was to introduce a new formalism to improve the understanding of phase errors and how they can be mitigated in dwSSFP.

METHODS & RESULTS: For simplicity we focus the discussion at a single voxel at location **r**, where the non-linear phase error is $\varphi(\mathbf{r}, i)$ with i being the i-th TR interval of a dwSSFP sequence. **Fig. 1** demonstrates how phase errors – accrued during individual TR intervals – propagate through individual coherences and contribute to the j^{th} echo. During each TR, a different phase $\varphi(\mathbf{r}, i)$ is accrued due to unpredictable motion during diffusion encoding. The phase from each TR is then distributed to the echoes formed in subsequent TRs. Thus, unlike a spin-echo that results from a single coherence path, each echo in dwSSFP is the superposition of complex magnetization arising from multiple pathways with potentially different accrued phase. While storage of diffusion preparation in the coherences is causative for strong diffusion-weighting despite the short diffusion-encoding gradients, it is also the source of dwSSFP's sensitivity to bulk motion. In the presence of physiologic motion, it leaves the net magnetization for each echo with an unpredictable phase and magnitude. Notice that these short encoding gradients lead to less phase errors and eddy currents than with Stejskal-Tanner preparation, which makes them easier to navigate and reconstruct.

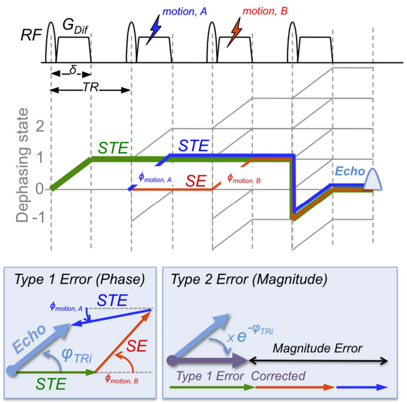

Figure 1 *– At each TR, the echo of a dwSSFP sequence is the weighted complex sum of all the zero-state coherences (i.e. those that cross the y=0 line). Any phase accrual due to motion in a single TR gets propagated (through multiple RF pulses) into* 3^N *coherences [5] until a subset (zero-state coherences) of them contribute to the echo in the* i^{th} *TR. The complex addition of all zero-state coherences with different phase errors from individual TRs will give a net echo signal that has a net phase* φ_{TRi} *(Type 1 phase error) and which will be different for each TR due to variable phase errors over time. The* φ_{TRi} *can be eliminated retrospectively by phase conjugation (Type 1 correction). However, the individual, phase-perturbed coherences that contribute errors to the* i^{th} *TR have accrued the phase term several TRs before. Thus, the signal magnitude will be lower due to destructive interferences (Type 2 phase error). Depending on the amount of interference, the magnitude signal will deviate more or less from the dwSSFP signal that is expected in the absence of motion (Magnitude Error). Note that these Type 2 phase errors can only be fixed within the TR they are occurring, i.e. prior to the next RF pulse.*

For each echo one can measure the net phase with a navigator and take the conjugate of this phase for phase correction (**Type 1 phase error**). This will eliminate ghosts in the reconstructed images that result from phase errors that conflict with regular phase encoding for imaging. However, the Type 1 phase correction done during image reconstruction cannot correct for the loss of magnitude caused by the destructive interference of previous coherences with differing motion-induced phases when reaching the zero dephasing state (**Type 2 errors**). Thus, in the presence of Type 2 errors, the diffusion coefficient appears to be higher because the motion-perturbed dwSSFP signal is lower than the dwSSFP signal without motion (**Fig. 2**). To correct for these errors, the phase error of each coherence needs to be corrected within the TR that this phase accrual actually occurs, i.e. before it gets passed on to subsequent dephasing states by the next RF pulse. Destructive interference of the coherences and the ability to correct for those can be shown in a phantom experiment where a phase error is artificially introduced by gradient blips. This phase error – measured via 3D navigator – can then be corrected by compensation blips and by adjusting the RF phase in real-time (**Fig. 3**).

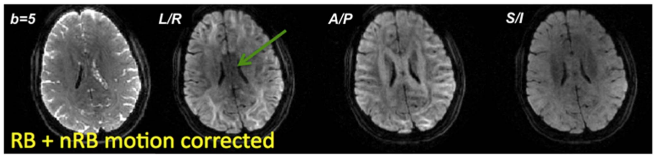

Figure 2 *– 3D dwSSFP [6]: from left to right: unweighted scan, b=800 along left-right, anterior-posterior, and superior-inferior direction. Type 1 (non-linear) phase correction takes care of image ghosts typically seen in DWI. However, signal amplitude in the S/I diffusion-weighted image as well as the L/R image (arrow) is lower than the A/P image due to considerable Type 2 phase errors that remained uncorrected.*

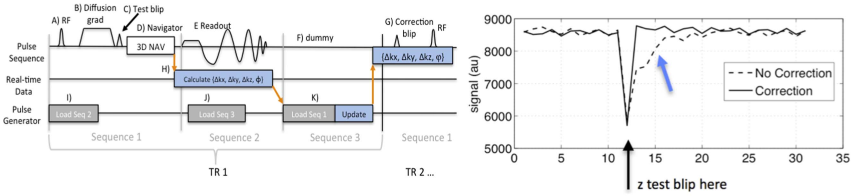

Figure 3 *– (left) dwSSFP sequence: a test gradient blip (C) introduces a phase error in the phantom that can be measured by the 3D navigator (D) and processed in real-time (K). Correction blips and RF phase adjustments can be played out for the next RF pulse (G). (right) Magnitude of k-space center of 3D spiral readout (E) plotted over time. In the absence of Type 2 correction (dashed line), when a test gradient blip is played (black arrow) at one TR, the phase error is propagated by the next pulse to different coherences and interferes destructively with subsequent echoes (blue arrow). With Type 2 correction (solid line), the signal returns immediately to the steady state signal. The residual dip is because the echo following the test blip does not see the correction blip. This can however be fixed via Type 1 phase correction (no interference).*

DISCUSSION & CONCLUSION: An intuitive description to understand the impact of phase errors in dwSSFP has been introduced. Theory and experiments demonstrate that Type 1 phase error correction – as usually done in interleaved acquisitions with regular Stejskal-Tanner preparation – is insufficient in dwSSFP, and that real time Type 2 phase correction is warranted to prevent phase errors propagating into higher coherence states. The Type 2 error also explains the puzzling lower signal (higher ADC) when diffusion-weighting is played along the S/I direction (**Fig. 2**) [2, 3]. In summary, understanding the complex interplay between Type 1 and 2 phase errors is crucial to substantially improve the image quality and quantitative accuracy of dwSSFP.

REFERENCES: [1] Buxton RB. *MRM* 29, 1993; [2] McNab, *et al*. *MRM* 60, 2008; [3] Miller KL, et al. *MRM* 51, 2004; [4] Alsop DC. *MRM* 38, 1997; [5] Hennig J, *Conc Magn Reson* 3, 1991; [6] O'Halloran RL, *et al*. *MRM*, 2012, early view. **Acknowledgements:** NIH (R01EB271108, R01EB8706, R01EB6526, P41EB15891), Lucas Foundation, Oak Foundation, and GE Healthcare.